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HANDLING QUALITIES OF LEM SPACECRAFT USING AN ON-OFF THRUSTER LOGIC ATTITUDE CONTROL SYSTEM

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HANDLING QUALITIES OF LEM SPACECRAFT USING AN ON-OFF THRUSTER LOGIC ATTITUDE CONTROL SYSTEM

SUMMARY

A piloted analog simulation of the final phase of lunar landing has been conducted by the Systems Analysis Branch, Guidance and Control Division. The purpose of this study was to determine the handling qualities of the LEM spacecraft having an on-off thruster logic attitude control system. Handling qualities of the vehicle were determined for the rate command and rate command-attitude hold modes of operation.

The study revealed that the present LEM control system provides satisfactory pilot handling qualities when operated in the rate command mode and unsatisfactory handling qualities when operated in the rate command-attitude hold mode. Two methods of improving handling qualities in the rate command-attitude hold mode are: 1) increasing the ratio of rate to attitude feedback and 2) increasing the deadband limits. However, both of these methods affect other system characteristics and it is suggested that the impact of these changes be determined.

INTRODUCTION

The handling qualities of the LEM spacecraft during the final approach to lunar landing have been investigated by in-house studies (ref. 1) and contracted studies (ref. 2). These studies, for the most part, have assumed the LEM employed linear proportional attitude control systems, although reference 1 did assume an upper limit to control power and thus, for large commanded rates and attitudes, the control systems exhibited some non-linear characteristics. Reference 1 does point out that linear systems will not in fact be used and attempts to correct the final results by use of an "equivalent time constant". However, the study results of reference 3 indicates the acceptance boundaries of reference 1 may be quite conservative for on-off thruster logic (equivalent to PRM logic for manual control). The reason for this, as noted in reference 3, is that for on-off thruster logic full control power is applied to correcting the attitude anytime the error signal is larger than the deadband. In a linear proportional system the control power applied to correcting an error is proportional to the error. The on-off thruster logic, then, corrects the error much more rapidly (approximately twice as fast) than the proportional system. Because of this rapid attainment of attitude change to commanded attitude, the pilot rating of the two systems having equal control power is lower (better) for the on-off logic than for the proportional system.

Unfortunately, the study of reference 3 was limited in scope and as a consequence only a portion of the required data of on-off logic handling qualities was determined. The data that have been determined needed to be expanded to clearly define the satsifactory region of this type of control system. The results of reference 3, however, are useful in that some of the parameters that must be varied have been fairly well defined.

To provide the necessary data, the Systems Analysis Branch, Guidance and Control Division, has conducted a piloted simulation of the final phase of lunar landing to define the handling qualities for this maneuver of attitude control systems employing on-off thruster logic. The attitude control systems modes investigated included rate command and rate command-attitude hold. The parameters examined were maximum rate command, control power, deadband, and ratio of rate to attitude feedback. Evaluation of these systems was made by experienced pilots using the Cooper Rating Scale.

DESCRIPTION OF SIMULATION

The simulation of the final phase of the lunar landing maneuver was accomplished by coupling an analog solution of the equations-of-motion to a fixed base LEM cockpit containing the pilot controls and flight instrument displays. The equations-of-motion (Appendix A) did not contain any orbital terms (flat "moon" assumption)since the velocities encountered during the landing maneuver are small. Mass of the LEM vehicle was assumed to be 450 slugs (approximately correct for present LEM during hover) and was held constant throughout a given run. The main engine of the LEM was assumed to have a continuous thrust variation from 1,050 to 10,500 pounds. A flow diagram of the complete simulation is given in figure 1.

Flight Instrument Displays

The instrument displays used in the simulation are shown in figure 2. In addition to these instruments, a 17-inch oscilloscope was used to depict downrange and crossrange distance of the LEM from the landing site. Movement of the dot corresponded to a PPI radar display. Information presented to the pilot on the other instrument was:

FDAI - Displayed attitude of the LEM with respect to the lunar surface

Altitude and Altitude Rate - Presented on two separate meters having selectable scales

Body Velocities - Body rates $\dot{y}$ and $\dot{z}$ were on two separate meters having selectable scales

Body Angular Rates - Pitch rate was presented on the vertical left hand and yaw rate on the horizontal needles mounted on the FDAI. Roll rate was on the meter located directly above the FDAI. Maximum rates were 15 degrees/second.

Thrust-to-weight-meter - Indicated ratio of main engine thrust to weight of the LEM

The selectable scales for the various instruments can be determined from figure 2.

Controllers

A Gemini type controller was used to make attitude changes of the vehicle. The main engine throttle control had essentially the same movements as the integrated throttle proposed for the LEM vehicle. However, the translational controller (T-handle) was not used in this simulation. The altitude and main engine throttle controllers are shown in figures 3a and 3b, respectively.

Control System

The control system used in this system was capable of operating in either a rate command or rate command-attitude hold mode as indicated in figure 4. Variables of the control system included maximum rate command (K_2) deadband, control power (M/I), and ratio of rate to attitude feedback (K_3). Hysteresis of the control system was assumed to be 10% of the deadband. Figure 4 is a block diagram of the pitch axis; the roll and yaw axes systems, except for commanded and controlled quantities, were identical to the pitch axis system.

TEST PROGRAM

The test program was flown by four pilots having military flight background and two research engineers having private piloting experience. The primary task given to the pilots consisted of flying the LEM vehicle from a hover condition at 200 feet of altitude to a landing site 1,000 feet
downrange and 500 feet crossrange. The pilots were required to touchdown
downrange and 500 feet crossrange. The pilots were required to touchdown with the main engine at idle cutoff with an altitude rate of less than

5 feet/second. Secondary tasks were used to cross check pilot opinions of the various control systems. One cross check task was to have the pilot maintain a hover condition for a specified length of time, the second task was to have the pilot fly in from a downrange of 3,000 feet and a crossrange of 500 feet.

Test Matrix

The test matrix was divided into two sections to investigate the two types of control systems. The pilots evaluated the entire rate command (RC) mode and then the rate command-attitude hold (RCAH) mode. A random selection of the various control system parameters was made to prevent the pilots from being able to anticipate the following control system characteristics. The parameters varied for the rate command system were:

1. Control Power
2. Maximum rate command
3. Deadband

Parameters varied for the rate command-attitude hold system were:

1. Control Power
2. Ratio of rate to attitude feedback
3. Deadband

The test matrix contained a total of 280 separate runs, approximately 200 for the RC mode and about 80 for the RCAH mode.

Control System Evaluation

Pilot evaluation of the two control modes was by means of the Cooper Rating System which is shown in table 1. Pilot performance during each run was recorded by time histories of vehicle and control system variables and an X-Y plot of crossrange vs downrange. End conditions of altitude rate, attitudes and attitude rates, translational velocities, and position error were recorded by the analog computer operator after each run.

DISCUSSION OF TEST RESULTS

The results as discussed in the following sections are based on the 280 runs made by six pilots. In general, the test subjects tended to agree with one another except at the higher control power levels. For control powers of greater than 50 deg/sec^2, the engineer test subjects rated the control systems higher (worse) than did the military-rated pilots. The only reason for this was apparently that the engineer test subjects did not care for violent eight-ball motions. By derating the control systems for this, the non-military pilots violated the ground rules since they were evaluating something that was not being investigated. However, the portion of the results so affected was relatively small and the overall results obtained should be accurate.

Rate Command Mode

Pilot ratings of all the rate command systems defined three distinct satisfactory regions corresponding to the three different deadbands used. These regions are shown in figure 5. The largest satisfactory region corresponds to the smallest deadband. As the deadband increased, the satisfactory region became progressively smaller. The upper part of the satisfactory boundary shown for a 0.1 deg/sec deadband was not actually determined as shown because the highest maximum rate command used was 100 deg/sec. If a higher maximum rate had been used for that deadband, the upper boundary might possibly have been higher, and in fact, might not even be closed as shown. The satisfactory regions for the other deadbands are, however, closed as shown.

A high control power could not be used efficiently with the larger deadbands because the sensitivity was too high for nulling the drift rate. This type of system always caused the pilot to overcontrol the high drift rate. When the 0.1 deg/sec deadband was used, however, small impulses were not required to constantly control the drift rate and a higher control power was desired.

Although the maximum rate command was varied up to 100 deg/sec, none of the pilots used much more than about 40 deg/sec at any time. In fact, it appeared that a maximum rate of 30 deg/sec was adequate for any of the control tasks given to the pilot in this simulation. Moreover, in cases where the control power was set at a low value (such as 5 deg/sec^2), a maximum rate of 30 deg/sec was higher than desired. With very low control power and a relatively high maximum rate, the pilot usually built up a rate too high for the control power available. This would result in overshooting the attitude desired. It is shown in figure 5 that a control power below 5 deg/sec^2 was always unsatisfactory no matter how the other parameters were varied. Also shown is the fact that control powers under

10 deg/sec^2 were always unsatisfactory when a deadband of 1 deg/sec was used.

For comparison, the satisfactory regions for 0.25 and 1 deg/sec deadbands obtained from reference 3 are shown in figure 5. It appears that some discrepancy exists between the results of this study and that of reference 3. However, it is believed that the study made in reference 3 was not thorough enough to obtain a true outline of the satisfactory regions.

Rate Command-Attitude Hold Mode

The results of the tests on rate command-attitude hold mode of operation have been divided into two deadbands - 0.1 degree and 1.0 degrees. Tests were also conducted for a 0.2 degree and a 0.5 degree deadband, but the results indicated there was no difference between the 0.1 and 0.2 degree deadband and 0.5 and 1.0 degree deadband. The satisfactory boundaries of pilot ratings obtained for this attitude mode are shown in figure 6a and 6b. Figure 6a shows the satisfactory region as determined for a deadband of 0.1 degree. As indicated in this figure, values of rate feedback below 1 required higher values of control power to make the system satisfactory. The reason for this is that low values of rate feedback caused the system to be quite oscillatory whereas high control powers tended to damp out the oscillations faster than low control powers. At values of rate feedback above 1.5, the pilots commented that the system was too sluggish, the result of the system being overdamped. Thus, a higher control power is desired when the rate feedback is high to make the system less sluggish. The 3.5 pilot rating boundary is open at the top because the control power was varied only up to 100 deg/sec^2.

Figure 6b shows the 3.5 pilot rating boundary for a 1.0 degree deadband. This boundary has the same general shape as the one for the 0.1 degree deadband. The main difference is that the lower left corner of the boundary for the 1.0 degree deadband goes to a lower value of rate feedback before it begins to curve upward. The reason for this is not clear. An examination of system response shows no essential difference for the 0.1 and 1.0 degree deadbands having equal control powers. The nominal frequency of the 1.0 degree is about 10% less and the nominal damping not more than 10% greater than a system having an 0.1 degree deadband. A pilot, in general, cannot discriminate between systems having characteristics this close together. A more thorough investigation of this phenomenon is necessary.

Impact of Study Results on LEM Spacecraft

The present LEM vehicle has a maximum rate command of 20°/second, a two jet control power of about 5.5 deg/sec^2, and selectable deadbands of 0.1 and 5.0 degrees. According to figure 5, the handling qualities of this system with a 0.1 degree deadband are barely acceptable. A four jet control system, which has a control power of 11 deg/sec^2, provides good handling qualities, but at the expense of increased attitude fuel consumption. Either two or four jet operation, then, provides the pilot with a satisfactory control system.

This, however, is not true for the rate command-attitude hold mode of operation. The present LEM spacecraft has a ratio of rate to attitude feedback of 1.2 during descent. From figure 6a, a control power of 5.5 deg/sec^2 and a ratio of rate to attitude feedback of 1.2 is outside the satisfactory region. Doubling the control power to 11 deg/sec^2 moves the operating point within to the satisfactory boundary, making the handling qualities just satisfactory. To obtain a satisfactory system with 5 deg/sec^2 requires a rate gain of at least 1.5 using a 0.1 degree deadband. Figure 6b, on the other hand, shows that increasing the deadband to 1.0 degree would provide a satisfactory system with a rate gain of 1.2 and a control power of 5.5 deg/sec^2; doubling the control power places the control system operating point well within the satisfactory region.

From this discussion, it is apparent that the rate command-attitude hold mode of control system operation should not be used unless the ratio of rate to attitude feedback or the deadband limits are increased. However, doing either one of these may not be practical since increasing the ratio of rate to attitude feedback affects other system characteristics while increasing the deadband probably compromises abort guidance performance. The effect of these changes on system characteristics should be determined.

CONCLUDING REMARKS

The results of this simulation verified the hypothesis that on-off thruster logic control systems produce better handling qualities with low control powers than do quasi-linear proportional control systems. At relatively high control powers, however, the handling qualities of these two systems in the rate command mode are about equivalent providing small deadbands are used in the on-off logic. For larger deadbands and large control powers, the handling qualities of the on-off system in a rate command mode deteriorate and the satisfactory region of operation is less than the proportional system.

Operation in a rate command-attitude hold mode indicated that the on-off logic also provided better handling qualities at low control powers than does the proportional control system. However, for the deadbands investigated in this study, no deterioration of handling qualities was noted as the deadband became larger. In fact, in some regions (that of medium ratios of rate to attitude feedback and low control powers) a large deadband gave better handling qualities than did the low deadbands. This phenomena is worthy of further investigation, particularly in view of the present LEM control powers.

The study also indicated the present LEM attitude control system provides satisfactory handling qualities in the rate command mode whereas in the rate command-attitude hold mode it exhibits unsatisfactory pilot handling qualities. The study results revealed that satisfactory handling qualities could be obtained by 1) increasing the ratio of rate to attitude feedback or 2) increasing the deadband limits to at least 1.0 degree. However, either of these two methods of improving handling qualities affects other system characteristics. The exact impact of these modifications on other system characteristics should be determined by analytical studies. If these studies indicate that these modifications cannot be tolerated, consideration should be given to deleting the rate command-attitude hold mode of control system operation in the LEM vehicle.

	ADJECTIVE RATING	NUMERICAL RATING	DESCRIPTION	PRIMARY MISSION ACCOMPLISHED?
NORMAL OPERATION	SATISFACTORY	1	EXCELLENT, INCLUDES OPTIMUM	YES
		2	GOOD, PLEASANT TO FLY	YES
		3	SATISFACTORY, BUT WITH SOME MILDLY UNPLEASANT CHARACTERISTICS	YES
EMERGENCY OPERATION	UNSATISFACTORY	4	ACCEPTABLE, BUT WITH UNPLEASANT CHARACTERISTICS	YES
		5	UNACCEPTABLE FOR NORMAL OPERATION	DOUBTFUL
		6	ACCEPTABLE FOR EMERGENCY CONDITION ONLY*	DOUBTFUL
NO OPERATION	UNACCEPTABLE	7	UNACCEPTABLE EVEN FOR EMERGENCY CONDITION*	NO
		8	UNACCEPTABLE - DANGEROUS	NO
		9	UNACCEPTABLE - UNCONTROLLABLE	NO
	CATASTROPHIC	10	MOTIONS POSSIBLY VIOLENT ENOUGH TO PREVENT PILOT ESCAPE	

*(FAILURE OF A STABILITY AUGMENTER)

Pilot opinion rating system.

Table I

References

1. Cheatham, D. C., and Moore, T. E., "Study of the Attitude Control Handling Qualities of the LEM During the Final Approach to Lunar Landing". NASA, Project Apollo Working Paper No. 1074, May 10, 1963.

2. Hill, J. A., "A Piloted Flight Simulation Study to Define the Handling Qualities Requirements for a Lunar Landing Vehicle". North American Aviation, Inc., Columbus Division, Columbus, Ohio, September 13, 1962, Report No. NA 62H-660.

3. Stubblefield, William, Cheatham, Donald C., Dyer, David A., and Cummings, William C., "A Simulation Study of the Landing-Approach Attitude Control Handling Qualities of the LEM Using On-Off Thruster Logic". NASA, Project Apollo Working Paper No. 1088, August 26, 1963.

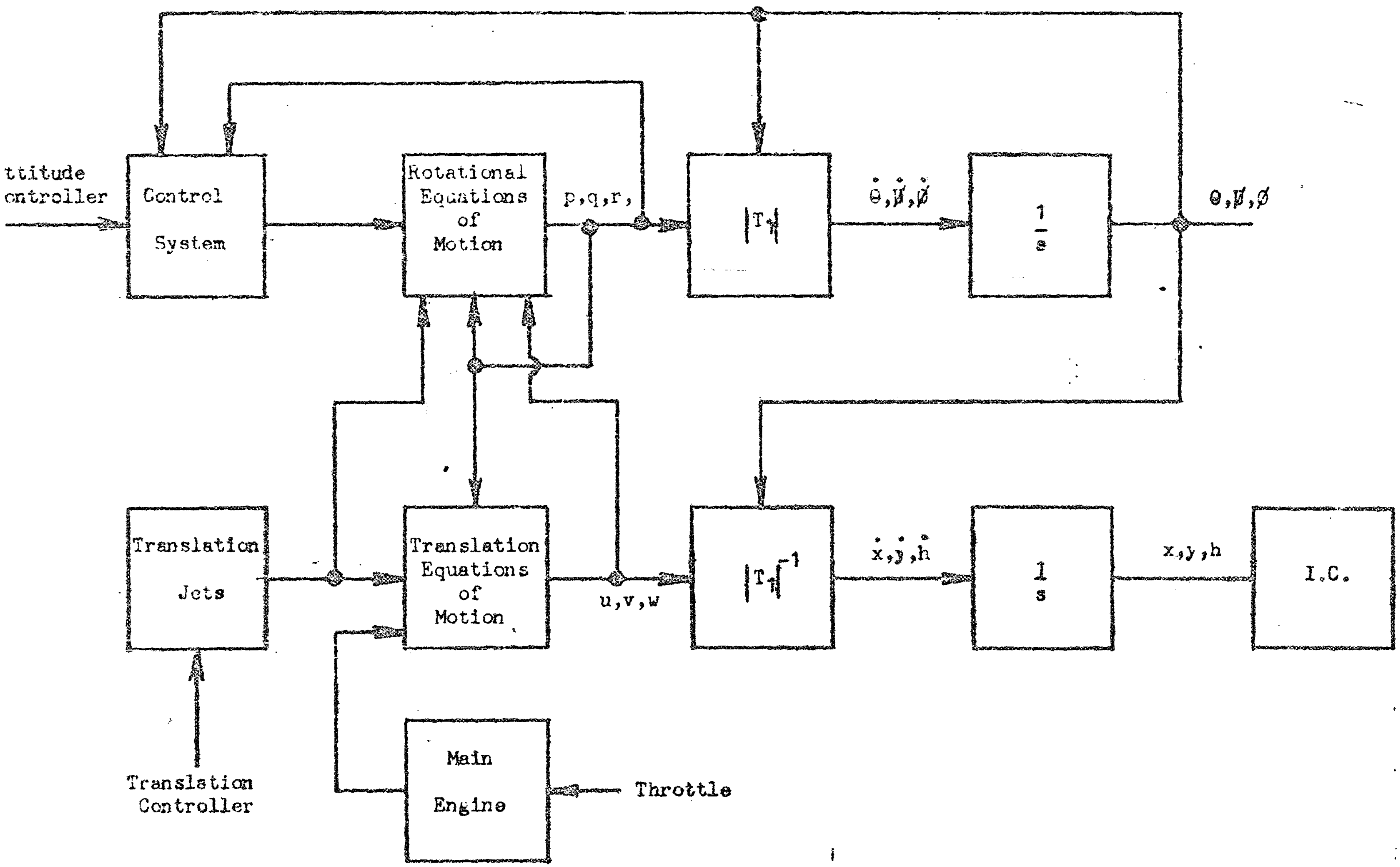


Figure 1 - Simulator Flow Diagram

Translation Equations

$$\dot{u} = \frac{F_x}{m} + rv - qw - g_m \cos\psi \cos\theta$$

$$\dot{v} = \frac{F_y}{m} + pw - ru - g_m(\sin\phi \sin\theta - \cos\phi \sin\psi \cos\theta)$$

$$\dot{w} = \frac{F_z}{m} + qu - pv - g_m(\cos\phi \sin\theta + \sin\phi \sin\psi \cos\theta)$$

where: $F_x = T_m$

$F_y = T_y + \delta_{\psi m} T_m$

$F_z = T_z - \delta_{\theta m} T_m$

Forward Velocity $= w = w_0 + \int \dot{w}\, dt$

Lateral Velocity $= v = v_0 + \int \dot{v}\, dt$

Altitude Rate $= \dot{h} = \dot{h}_0 + u \cos\psi \cos\theta +$

$$v(\sin\phi \sin\theta - \cos\phi \sin\psi \cos\theta) +$$

$$w(\cos\phi \sin\theta + \sin\phi \sin\psi \cos\theta)$$

Altitude $= h = h_0 + \int \dot{h}\, dt$

Inputs To CRT

Down Range $= Z_p = \int \Big[-u \cos\psi \sin\theta + v(\sin\phi \cos\theta +$

$$\cos\phi \sin\psi \sin\theta) + w(\cos\phi \cos\theta -$$

$$\sin\phi \sin\psi \sin\theta) \Big] dt$$

$$\text{Cross Range} = Y_p = \int \left[u \sin\psi + v \cos\phi \cos\psi - w \sin\phi \cos\psi \right] dt$$

Rotation Equations (θ, ψ, ϕ)

$$p = \int \frac{1}{I_x} \left[L - (I_z - I_y) q r + p \dot{m} \, l^2_{DPD} \right] dt$$

$$q = \int \frac{1}{I_y} \left[M - (I_x - I_z) p r + q \dot{m} \, l^2_{DqrD} \right] dt$$

$$r = \int \frac{1}{I_z} \left[N - (I_y - I_x) p q + r \dot{m} \, l^2_{DqrD} \right] dt$$

where: $L = M_{cp}^{*} - T_m (y_m \delta_{\theta m} + z_m \delta_{\psi m})$

$M = M_{cq}^{*} + T_z X_1 + T_m (z_m + X_m \delta_{\theta m})$

$N = M_{cr}^{*} + T_y X_1 + T_m (X_m \delta_{\psi m} - y_m)$

* control moment

$\dot{m} = T_m / g_m I_{sp}$

$$\theta = \int \sec\psi \, (q \cos\phi - r \sin\phi) \, dt$$

$$\psi = \int (r \cos\phi + q \sin\phi) \, dt$$

$$\phi = \int \left[p - \tan\psi \, (q \cos\phi - r \sin\phi) \right] dt$$

ΔV and Fuel Equations

Translation:

$$\Delta V = \int \frac{T_m}{m}\, dt \qquad \text{(decent engine)}$$

$$\Delta V = \int \frac{(|T_y| + |T_z|)}{m}\, dt \qquad \text{(RCS jets)}$$

Rotation:

$$W(lbs) = \int \frac{\left(\left|\frac{M_{cp}}{l_p}\right| + \left|\frac{M_{cq}}{l_q}\right| + \left|\frac{M_{cr}}{l_r}\right|\right)}{I_{sp}(RCS)}\, dt$$

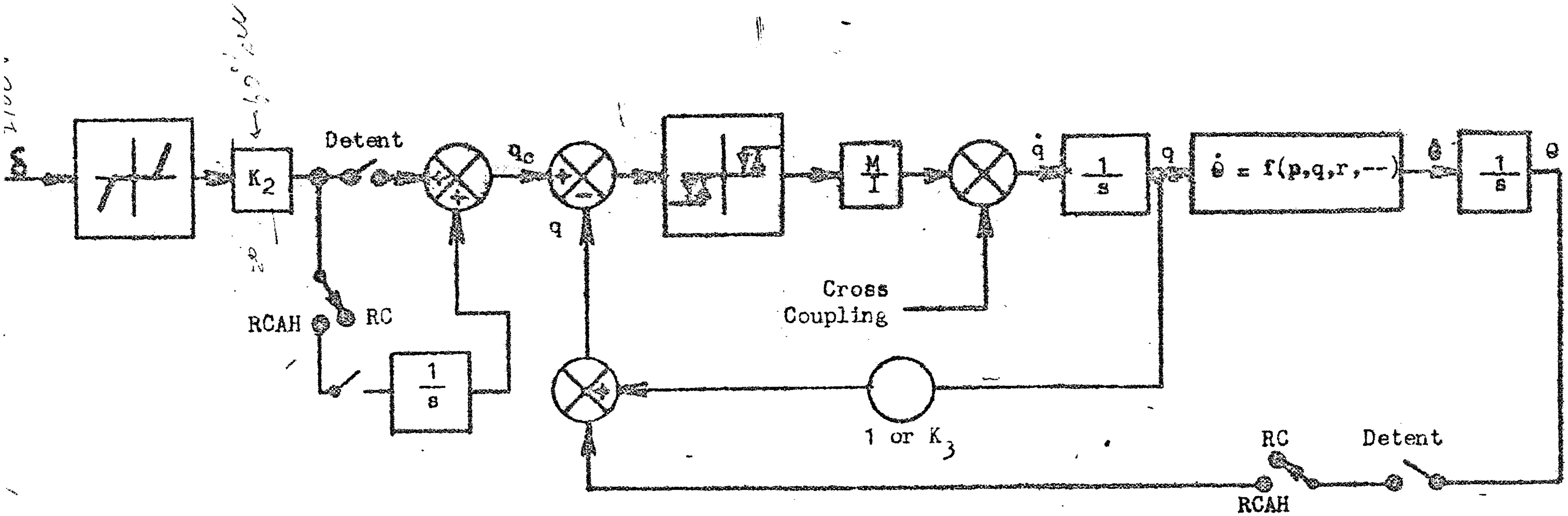


Figure 4 - Pitch Channel Control System

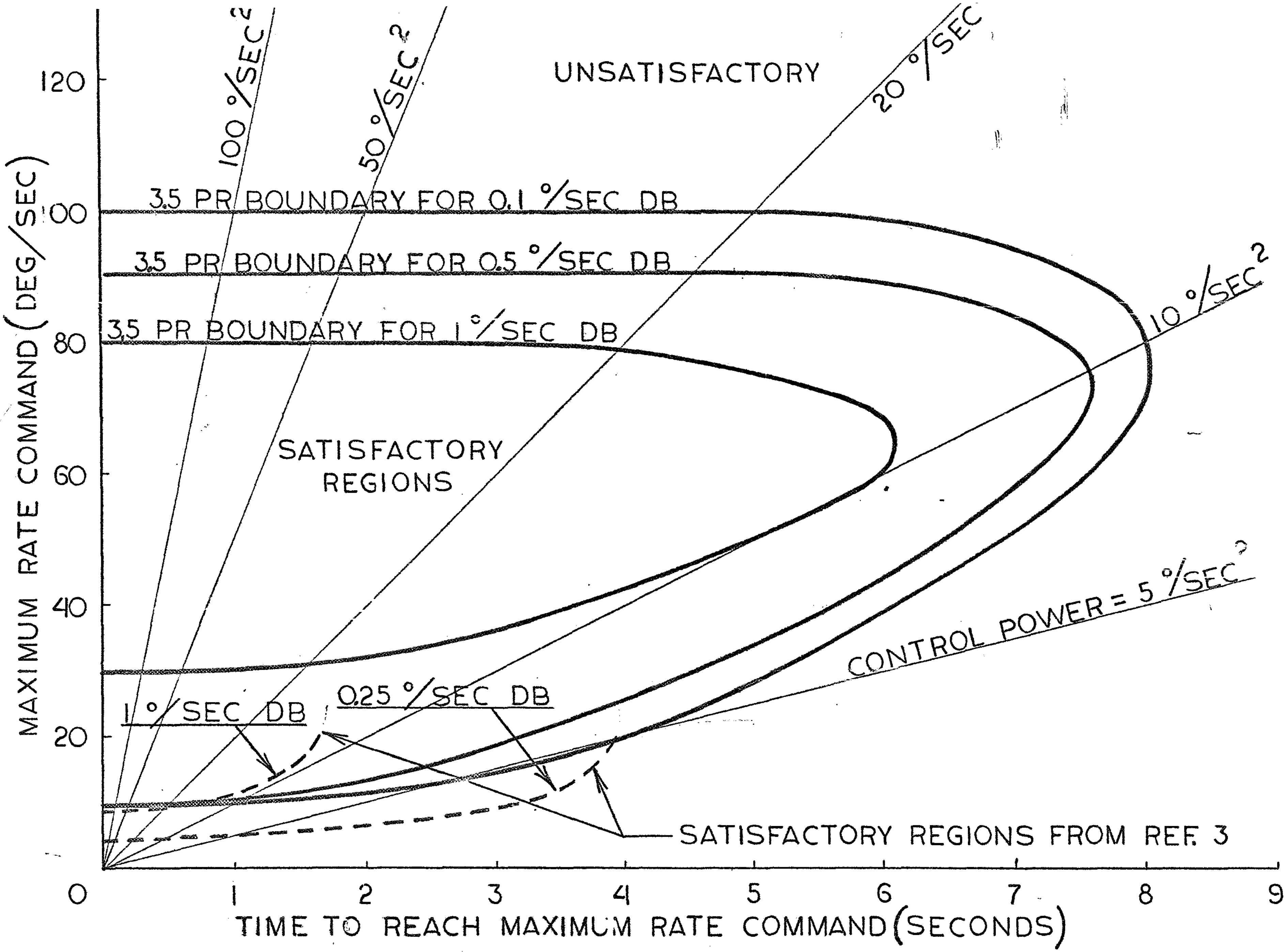


FIGURE 5 – PILOT RATING OF RATE COMMAND SYSTEMS

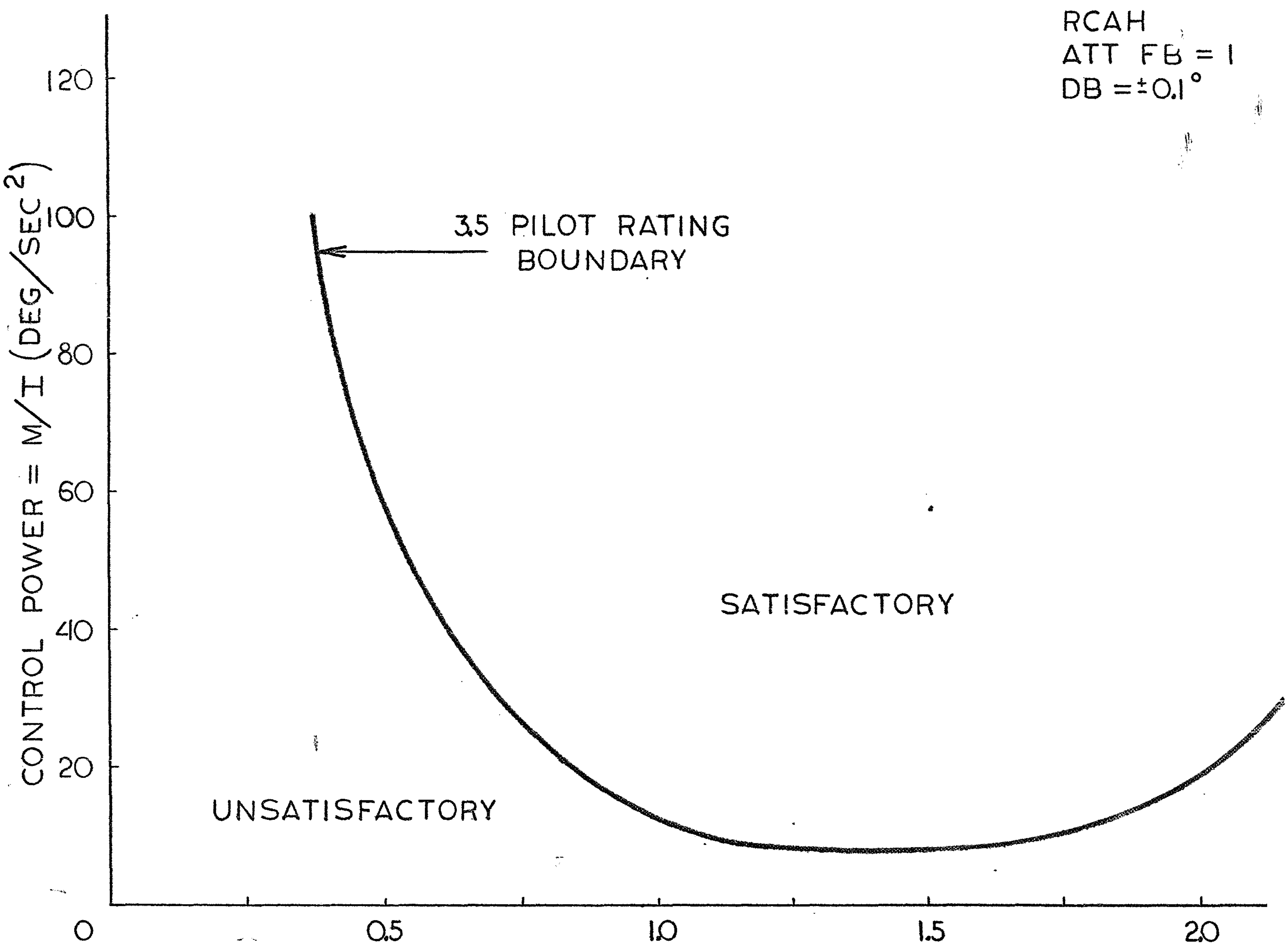
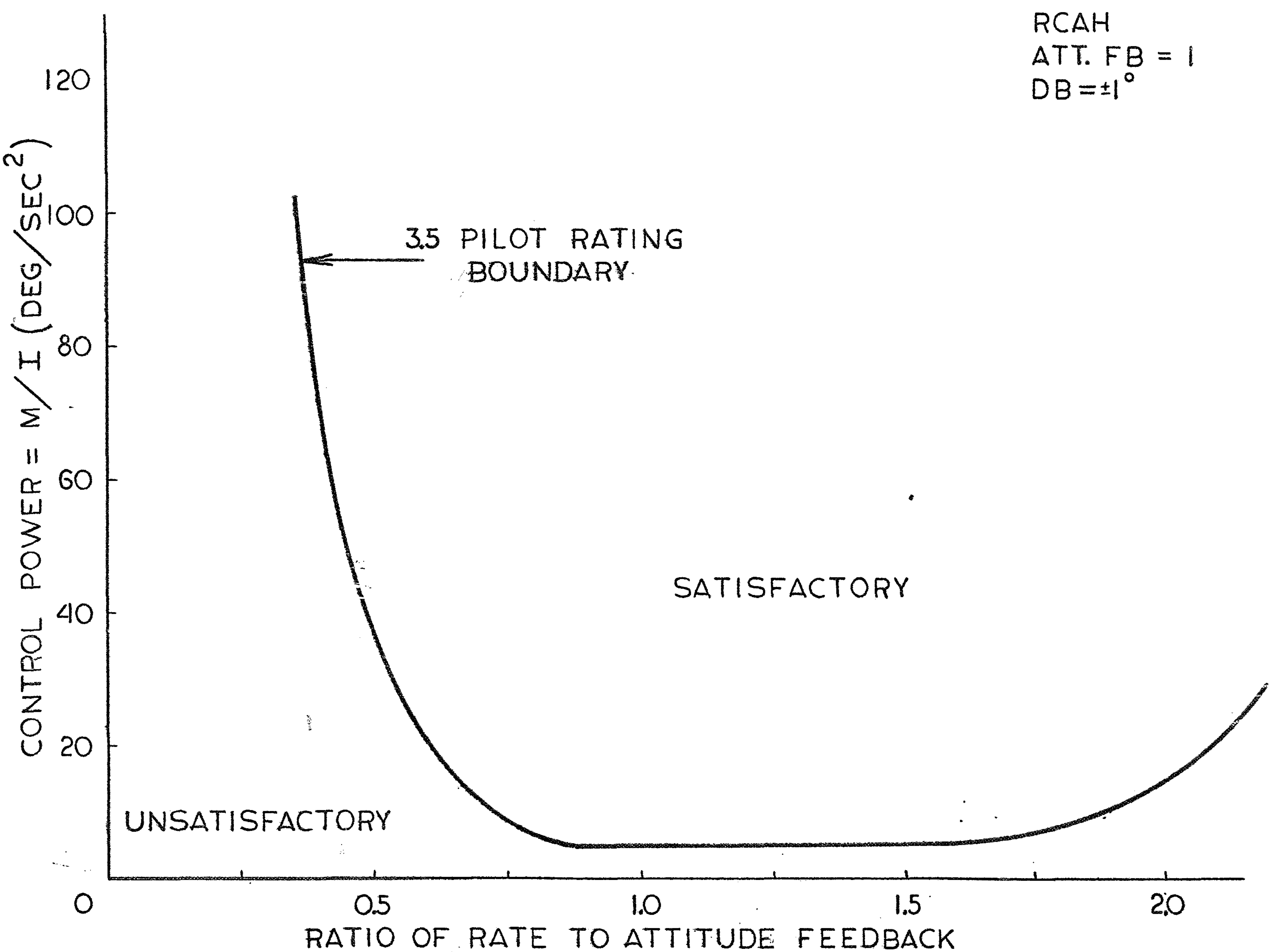


FIGURE 6 – PILOT RATING OF ATTITUDE HOLD SYSTEMS
(A.) – 0.1 DEGREE DEADBAND



(B.) - 1 DEGREE DEADBAND

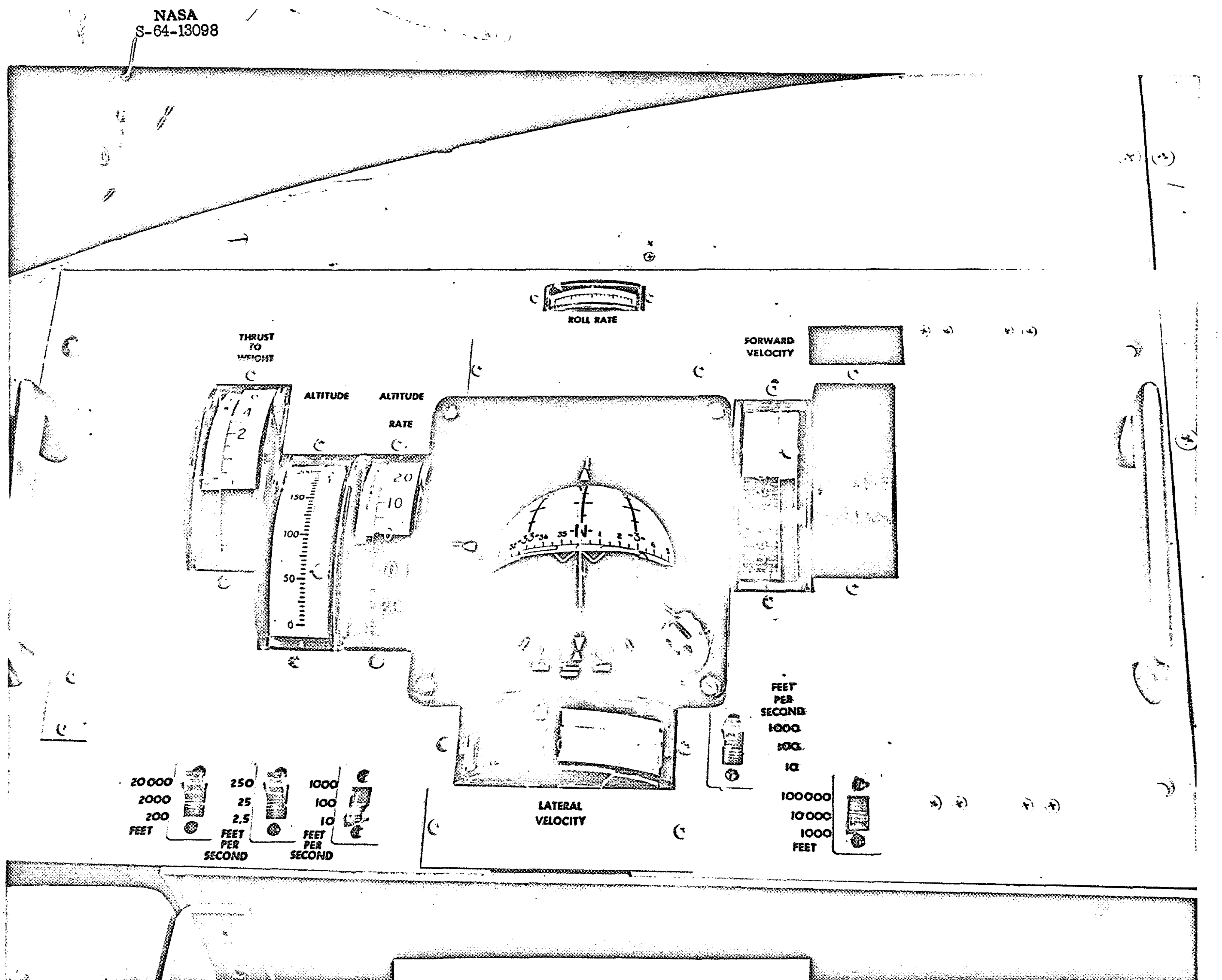


Figure 2. Pilot Instrument Panel

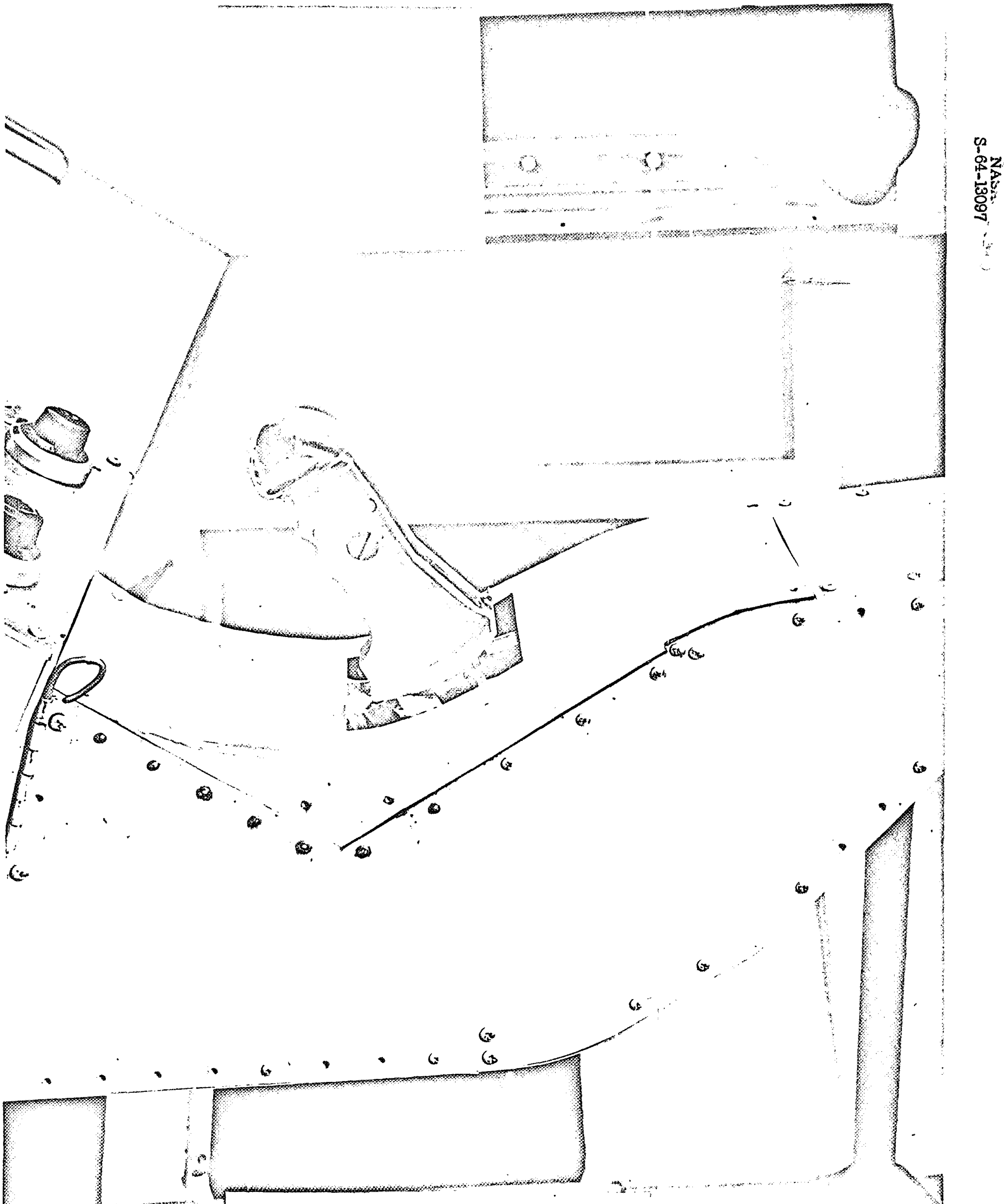


Figure 3a - Attitude Controller
Pilot Controls

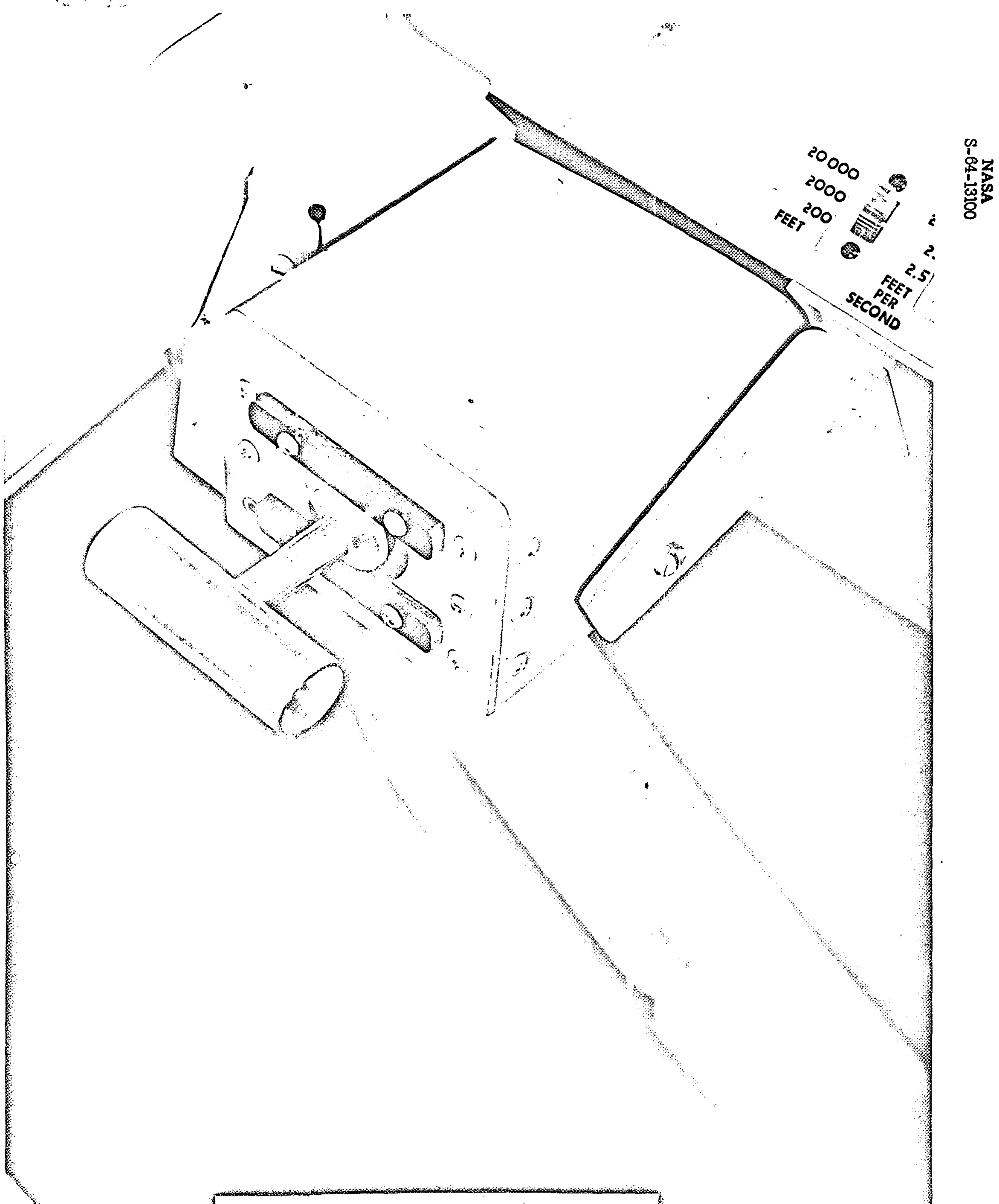


Figure 3b - Throttle Controller